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L. F. BURLAGA

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GODDARD SPACE FLIGHT CENTER
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# DISCONTINUITIES AND SHOCK WAVES IN THE INTERPLANETARY MEDIUM AND THEIR INTERACTION WITH THE MAGNETOSPHERE*

Leonard F. Burlaga
Laboratory for Extraterrestrial Physics
NASA-Goddard Space Flight Center
Greenbelt, Maryland USA

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## Abstract

The discontinuous structure of the solar wind is described with emphasis on properties related to geomagnetic impulses. Some of the discontinuities are clearly hydromagnetic shocks and tangential discontinuities, and can produce a significant change in the momentum flux at the magnetosphere boundary. Such a change generates an impulse which propagates through the magnetosphere to the earth where it is observed world-wide as an impulse in magnetograms. The propagation process is not reviewed here, but the relation between the initial cause (discontinuity) and the final effect (geomagnetic impulse) is reviewed in detail. The various types of impulses are examined, and are related qualitatively to the various types of discontinuities. The magnitude of an impulse is related to the change in the momentum flux. The propagation time and the rise time depend on the propagation process rather than on the initial state. Double shocks have not been observed, but a reverse shock has been identified. Giant pairs can be caused by a shock followed by a tangential discontinuity, and regular pairs may be due to complementary tangential discontinuities.

## I. Introduction

Impulsive changes in the geomagnetic field have been extensively studied for many years. Several types have been identified and much is known about their morphology, but the results are somewhat obscured by the proliferation of different and sometimes conflicting notations. There are also many speculations in the literature, some correct and some incorrect, concerning the causes of the impulses.

The advent of space probes has led to the discovery of several kinds of hydromagnetic discontinuities in the solar wind, some of which were shown to cause geomagnetic impulses. In principle, it is now possible to determine unambiguously the causes of geomagnetic impulses and the effects of interplanetary discontinuities on the earth's field. Many correlations have already been published.

The aim of this review is to present a synthesis of the published observations which definitively shows the relations between interplanetary discontinuities and geomagnetic impulses. The work necessarily falls short of this goal because the observations are incomplete, but the shortcomings show where effort should be concentrated in future observational studies.

Section II presents a summary of work concerning the interplanetary discontinuities with an emphasis on properties relevant to the study of geomagnetic impulses. Section III gives a summary of the types of geomagnetic impulses, and emphasizes the kinds of impulses that unambiguously occur world-wide. Sections IV then reviews the simultaneous observations of geomagnetic and interplanetary discontinuities. The geomagnetic impulse is regarded as a final effect and the interplanetary discontinuity as an initial cause and we aim at showing the relations between them.

## II. Interplanetary Discontinuities

### A. Existence of Hydromagnetic Discontinuities in the Solar Wind.

Direct measurements of the solar wind show that the magnetic field and plasma parameters may change by more than 50% over a distance of $\sim 10^{-5}$ AU. Such a change is essentially discontinuous on a scale of 1 AU, or even on a scale of .01 AU where it is seen most clearly (see Figure 1). It is found that at least some of these changes have the characteristics of hydromagnetic discontinuities. The mere existence of such discontinuities is not surprising, for they were predicted long ago from the equations of magnetohydrodynamics. However, it is of fundamental significance that such discontinuities occur in the interplanetary plasma, which is essentially collisionless. This shows de facto that theory of magnetohydrodynamics is applicable (at least in some instances) to the solar wind at 1 AU, and reveals an extension of the fluid concept.

Possible types of hydromagnetic discontinuities in an isotropic plasma are as follows:

1) tangential discontinuities (T.D.'s)
2) contact surfaces
3) rotational discontinuities (R.D.)
4) fast shocks
5) slow shocks

These are discussed formally in various textbooks (Landau and Lifshitz, 1960; Ferraro and Plumpton, 1966), and reviews (Colburn and Sonett, 1966; Spreiter and Alksne, 1969), so we need not go into the mathematical details. We shall, however, discuss the qualitative characteristics of the different types of discontinuities, their significance with respect to geomagnetic impulses, and their existence in the solar wind.

The concept of a tangential discontinuity is illustrated in Figure 2. It is an observable surface (a current sheet in fact) that separates 2 physically distinct plasmas. On both sides there is a magnetic field which is parallel to the surface but otherwise arbitrary. The plasma and magnetic field on each side can have any value, subject to the constraint that the pressure, $\sum_i n_i kT_i + B^2/(8\pi)$ (the sum is over all particle species), is the same on both sides of the discontinuity. A T.D. does not propagate relative to the solar wind, i.e., there is no mass flux through the surface. But the material on side 1 can move relative to that on side 2 along the surface (hence the term "glide plane" for the surface- Burlaga, 1969). Burlaga (1968) has classified T.D.'s into 13 types, according to the sign of the change in B, proton density (n), and proton temperature (T). The symbol (+,-,0) denotes an increase in B, a decrease in n, no change in T; (0,+,-) means no change in B, an increase in n, a decrease in T; etc. It should be emphasized that such a signature is not a sufficient condition for identification of a T.D. A change in momentum flux of the solar wind relative to the earth, $\Delta(nmV_W) \approx mV_W \Delta n$, occurs across T.D.'s with signatures (x, $\pm$, y). Such T.D.'s can produce geomagnetic impulses if n is sufficiently large; those with signatures (x,o,y) cannot. (A small change in $V_W$ may be observed across a T.D. due to motions along the glide plane, but they do not produce significant impulses). Direct evidence for hydromagnetic tangential discontinuities in the solar wind was presented by Burlaga (1968) and Burlaga and Ness (1969), and current sheets characteristic of those at T.D.'s were identified by Siscoe et al. (1968a).

A contact surface is frequently confused with a T.D. since both are non-propagating and the pressure is continuous across both. But there is a fundamental difference: there is a component of $\underset{\sim}{B}$ normal to a contact surface and $\underset{\sim}{B}_1 = \underset{\sim}{B}_2$, whereas at a T.D. $\underset{\sim}{B}$ is parallel to the surface and in general $\underset{\sim}{B}_1 \neq \underset{\sim}{B}_2$. There can be no relative motions of the 2 regions separated by a contact surface, so $\underset{\sim}{V}_{w_1} = \underset{\sim}{V}_{w2}$. Contact surfaces could give rise to geomagnetic impulses, since $n_2 \neq n_1$ (the pressure is balanced by a corresponding change in the temperature), but none has yet been identified in the solar wind. Two spacecraft are needed to distinguish a contact surface from a T.D. with signature $(0, \pm, \mp)$ and $\underset{\sim}{B}_1 = \underset{\sim}{B}_2$.

**Rotational discontinuities** are so named because the component of $\underset{\sim}{B}$ tangent to the discontinuity surface, $\underset{\sim}{B}_t$, appears to rotate across the surface, without changing magnitude (see Figure 3). There is a corresponding change in the velocity, $[\underset{\sim}{v}_t] = [\underset{\sim}{B}_t] /(4\pi\rho)$, but n, B, T do not change across the surface. The discontinuity surface actually moves at the Alfven speed $V_\perp = B_\perp/4\pi\rho$ in the direction of its normal. Thus there is a mass flux through it. For this reason, it is sometimes referred to as a kind of shock; this is misleading, however, since there is no change in n, T and v as in a shock, and $\hat{n}$, $\hat{B}_1$, $\hat{B}_2$ are not coplanar as they are for a shock. It is better to picture a rotational discontinuity as a non-linear Alfven wave, or a propagating kink in the magnetic field. Since $v_t \ll V_W$ (the solar wind speed), and since $\Delta n = 0$, the change in momentum flux across an R.D. is small $\Delta(mnV) \approx \rho\Delta V \approx \rho V_W \frac{[v_t]}{V_W}$ and is not likely to produce an observable geomagnetic impulse (see Section IV). Belcher et al. (1969) presented solar wind observations which are consistent with R.D.'s, but they could also be interpreted as T.D.'s. It is very difficult to distinguish an R.D. from a T. D. of the type (0,0,0), even if the solar wind direction is accurately known. The relative number of R.D.'s and T.D.'s in the solar wind is thus not known, but it is likely that most discontinuities are tangential.

Fast shocks are analogous to ordinary gasdynamic shocks, the difference being that across a fast shock the magnetic field intensity increases as well as the density and temperature. Relative to the shock speed, the flow speed decreases across the shock, i.e., $v_b < v_f$ (b = behind the shock, f = ahead of it). When a fast shock propagates away from the sun, as is usually the case in the solar wind, $v_f = U - V_f$ and $v_b = U - V_b$, where U and V are the shock speed and the solar wind speed, respectively, relative to the sun; thus $v_b < v_f$ $V_b > V_f$. In other words the solar wind speed measured relative to a fixed frame appears to increase across a fast shock moving away from the sun. Now, it is also possible for a fast shock to propagate toward the sun, yet move away from it, if it propagates slower than the solar wind speed. (It's like a man trying to walk slowly up a "down" escalator). In this case one first sees the flow behind the shock, so n, B and T appear to decrease with time. The speed always decreases behind the shock, so $v_f = U+V_f > v_b = U+V_b$ implies $V_f > V_b$. Since one first sees the flow behind this shock ($V_b$), the solar wind speed appears to increase with time. A fast shock propagating toward the sun is called a "reverse shock". Summarizing, a fast shock moving outward has the signature (+, +, +) and V increases, while a "reverse fast shock" has the signature (-, -, -) and V increases. The momentum flux relative to the earth increases across a fast shock moving away from the sun, and decreases across a "reverse fast shock". The existence of fast shocks in the solar wind has been established with increasing certainty by Sonett et al. (1964), Ogilvie and Burlaga (1969) and Chao (1970), respectively. The existence of a reverse shock in the solar wind has recently been established by Burlaga (1970).

Slow shocks are characterized by an increase in n,T and V and a decrease in B. Chao (1970) has reported evidence for 2 slow shocks in the solar wind. They do not show the discontinuous changes characteristic of fast shocks.

For a list of shocks and discontinuities that might be shocks see Hundhausen (1969).

B. General Properties of Interplanetary Discontinuities.

Usually one does not have enough information to unambiguously identify the type of discontinuity. Certain general features of interplanetary discontinuities can be studied nevertheless. The statistical characteristics of discontinuities in the interplanetary magnetic field have been studied by Siscoe et al. (1968a), Burlaga and Ness (1968), Burlaga (1968, 1969). Two quantities are of special interest with regard to geomagnetic impulses: 1) the distribution of time intervals between successive discontinuities seen at a fixed spacecraft, and 2) the distribution of the change, $\Delta B$, in the magnitude of $\underset{\sim}{B}$ across discontinuities.

Let $\omega$ be the change in the direction of $\underset{\sim}{B}$ across discontinuities. Siscoe et al. (1968a) defined a discontinuity by the condition $|\underset{\sim}{B}(t_2) - \underset{\sim}{B}(t_1)| \geq 4\gamma$, which implies $\omega \gtrsim 20^{\circ}$ for $|\underset{\sim}{B}_1| = |\underset{\sim}{B}_2| \sim 6\gamma$ Burlaga studied "directional discontinuities" defined by $\omega > 30^{\circ}$. Both assume that the change occurs in $\lesssim 1$ minute. The 2 definitions are equivalent if $B_1 \sim B_2 \gtrsim 4\gamma$, as is usually the case.

Figure 4a shows the distribution of $B_1/B_2$ for 114 "planar" discontinuities (i.e. discontinuities which appear to be tangential) with thickness 10 sec $< T < 100$ sec from the Mariner 4 data for the period November 30, 1964 to January 3, 1965. Figure 4b shows the corresponding distribution of $(B_1 - B_2)/\mathrm{Max}(B_1, B_2)$ for all the directional discontinuities from Pioneer 6 data for the period December 15, 1965-January. Although they are not strictly comparable, since Max $(B_1, B_2) = B_2$ only half of the time, the 2 distributions do show the same results, viz., a) the magnitude, B, usually does not change significantly across a discontinuity, and b) increases and decreases of B across the discontinuity are equally probable. The similarity between the Mariner and Pioneer results suggests that they refer to basically the same type of structures and indicates that the characteristics did not change appreciably during the year between the two measurements.

Siscoe et al. (1968a) found that "discontinuities" (actually current sheets) defined by $|B_2 - B_1| \geq 4\gamma$ occur roughly at the rate of 1 per hour at quiet times. This does not completely describe the time distribution, since there are many discontinuities with $|B_2 - B_1| < 4\gamma$ which occur even more frequently than 1/hour. Burlaga divided the discontinuities into 4 classes and obtained the distributions shown in Figure 5 for the time intervals between successive discontinuities in each class. The discontinuities with $30^\circ < \omega < 60^\circ$ occur with a mean separation 2 hour. Smaller discontinuities ($\omega < 30^\circ$) occur more often, but are more difficult to identify and measure.

Unfortunately, there are as yet no distributions for the <u>discontinuities in plasma parameters</u>, n, V and T, corresponding to the magnetic field distributions described above. There are at least 2 reasons for this: 1) the plasma parameters are not measured as accurately as the magnetic field, and 2) the time between successive measurements is relatively long, usually 1 min-5 min, so that it is difficult to distinguish small discontinuities from continuous changes. It may also be found that the changes in plasma parameters are not as abrupt as changes in the magnetic field direction. Since the desired distributions are not likely to be forthcoming for sometime, yet are of basic importance for studying small impulses in the earth's magnetic field, we shall venture to make some order of magnitude estimates. Suppose that most discontinuities are tangential discontinuities, so that $B^2/8\pi + nk(T_p+T_e) =$ const., and suppose that $(T_p+T_e) \sim$ constant for most discontinuities. Then, assuming $\beta = nk(T_p+T_e)/(B^2/8\pi) \approx 1$,

$2\frac{\Delta B}{B} \sim \frac{\Delta n}{n}$ , and a 40% change in n will be caused by a 20% change in B. Figure 4 shows that B changes by $\gtrsim$ 20% for ~25% of the directional discontinuities. Since directional discontinuities occur at the rate of ~1/(2 hour), we expect density changes to occur at the rate of ~1/(8 hr), or 3/day, with increases and decreases being equally probable. There are times when density discontinuities may occur more frequently. For example, Siscoe et al. (1968a) and Burlaga (1969) showed a series of density discontinuities following a shock which was apparently driven by a high speed stream (See Figure 6). Changes in the bulk speed may occur, but will probably be small ($\lesssim$ 5%) for most discontinuities. A study of large changes in the bulk speed by Burlaga (1969) showed only 6 cases with $\Delta V > 60$ km/sec in ~2500 hours of data; thus, discontinuities with $\frac{\Delta V}{V} \gtrsim 15\%$ occur roughly at the rate ~1/15 days. Such discontinuities are not important as regards geomagnetic impulses.

C. Filaments and Sector Boundaries.

The discovery of numerous discontinuities in the magnetic field direction and magnitude (Ness et al., 1964, 1966) and in the direction of anisotropic cosmic ray fluxes (Bartley, et al., 1966) led to the suggestion that the interplanetary magnetic field could be pictured as a bundle of corotating, intertwined, spaghetti-like "tubes" or filaments with sharp boundaries which extended from the sun to the earth's orbit and beyond (McCracken and Ness, 1966). The diameters of these tubes was put at (.5 to 4) x $10^6$km. Additional support for this appealing picture was given by Siscoe et al. (1968a) who suggested that the tubes are actually elliptical as the result of latitudinal solar wind shear.

Hundhausen et al. (1967 a,b) reported discontinuous changes in the plasma parameters and interpreted this as boundaries of filaments with a scale size near a hundredth of an AU.

This picture of filaments grew out of preliminary work based on small data samples. Burlaga (1968) examined 500 hours of magnetic field data from Pioneer 6 and pointed out that discontinuities were always present and could be quantitatively defined and analyzed, but filaments could not always be recognized or defined. For example, Figure 7 shows a quiet day with 11 clearly defined directional discontinuities, but the identification of filaments would be very subjective. He also noted that in general there is no obvious pairing of discontinuities. Thus, Burlaga suggested that the solar wind should be regarded as discontinuous rather than filamentary and he pointed out that one should not discard the possiblity that discontinuities are created and destroyed in the interplanetary medium.

There are occasional times, however, when filamentary forms can be seen, particularly behind shocks (see Figures 1, 6), but these forms are not always bounded by sharp discontinuities. The class of "box-like" events discus... by Siscoe et al. (1968a) and those of Ness et al. (1966, Figure 8) might also be properly termed filaments. The behavior of **isolated filaments** has been investigated analytically by Siscoe (1970).

There is as yet no general, quantitative definition of a filament. Until one is given, it might be better not to speak of the radius of filaments or the topology of filamentary magnetic tubes.

The boundary between sectors (Ness et al. 1969, Wilcox and Ness, 1965) is sometimes discontinuous. Several authors have given special geophysical significance to these boundaries but their importance is probably overestimated. Sector boundaries are not always discontinuous or well defined, particularly during the more active parts of the solar cycle (Burlaga and Ness, 1967, Ness and Wilcox, 1967); but neither are they "turbulent". When they are discontinuous, it is usually a directional discontinuity with no change in the magnitude of $\underset{\sim}{B}$, so there is generally no corresponding geomagnetic impulse. Nishida (1966a) discusses a positive "sudden impulse" (not reported by geomagnetic observatories) associated with a sector boundary. This directional discontinuity was associated with a dip in the magnetic field intensity, and thus has the character of a "D-sheet". Such structures were studied by Burlaga and Ness (1968) and Burlaga (1968) who find that they do not always occur at sector boundaries, and that they are accompanied by an increase in density; thus, they could produce a geomagnetic impulse as suggested by Nishida (1966a), but not all sector boundaries would give such an impulse, and such impulses may occur in the absence of sector boundaries.

## III. Types of Geomagnetic Impulses

Several types of impulses are seen in ordinary magnetograms, usually most clearly in the H component of the earth's magnetic field. The Provisional Atlas of Rapid Variations (1957) classifies the impulses as $si^{\pm}$, $ssc^{\pm}$, and $ssc^{*}$. These are illustrated in Figure 8 and defined as follows:

1) $si^{\pm}$ (a) An abrupt increase (+) or decrease (-) in the magnetic field which is not followed by an appreciable increase in activity, (b) a small reversed impulse, not followed by an increase in activity, and (c) a large, distinctive impulse similar to (a) above except that it occurs during a storm.

2) $ssc^{\pm}$ (a) a sudden impulse (positive +, or negative -), followed by an increase in activity lasting at least one hour. The intense activity of the storm may appear immediately or it may be delayed a few hours, (b) a reverse impulse followed by an increase in activity.

3) $ssc^{*}$ (a) an ssc which is preceded by one reversed small impulse or (b) preceded by many small oscillations.

These are the principal types of impulses reported by observatories following the IAGA Symposium on Rapid Magnetic Variations in April 1957. See the Provisional Atlas for further details and additional examples. Observatories were asked to evaluate their identification of an impulse by the letters A (very distinct), B (fair, ordinary, but unmistakable) and C (doubtful). This is useful when deciding how to classify an event using all of the world-wide data.

The distinction between ssc and si was first suggested by Chapman (see Ferraro et al., 1951).

Other classifications of geomagnetic impulses have been proposed (see Matsushita 1960, p. 1425 for references). Of special interest is that of Matsushita (1962) who distinguishes 3 types of sudden commencements ($^{-}$SC, SC, and SC$^{-}$) and 3 completely analogous types of sudden impulses ($^{-}$SI, SI, SI$^{-}$). The superscripts refer to small impulses preceding or following the main impulse which are found to be dependent on latitude and time, the dependence being the same for sudden commencements and sudden impulses. In the literature concerning spacecraft data these secondary pulses are often ignored since they are due to ionospheric currents, and one frequently finds the symbols SSC or SC and SI denoting the 2 general classes of impulses distinguished by Matsushita. Matsushita distinguishes a fourth type of sudden impulse SI$^{\ominus}$ which differs from SI$^{-}$ in that it occurs simultaneously in the same form at all points on the earth. He points out that there is no analogous SC$^{\ominus}$, an important point which is discussed in Section IV. The currents which give rise to the various types of sudden commencements are discussed by Sato (1961) and by Sastri and Jagakar (1967).

Clearly, the Atlas classifications depend on local time and latitude, and are also subjective, so not all stations will report the same result. Thus, one cannot in general simply characterize the world-wide observations simply and unambiguously by any one of the symbols above. Burlaga and Ogilvie (1969) introduced the symbol

$$A \equiv \frac{N(ssc)-N(si)}{N(ssc)+N(si)}$$

where N(ssc) and N(si) are, respectively, the number of stations that report an event as a type of sudden commencement, and the number reporting it as a sudden impulse. For events which according to Solar Geophysical Data were classified as a sudden commencement or sudden impulse by 10 or more observatories and occurred in the interval June-December 1967, Burlaga and Ogilvie (1969) found the distribution shown in Figure 9. Clearly, there are 2 classes corresponding to sudden commencements ($A \geq .8$) and sudden impulses ($A \leq .8$), but there are also many events that do not fall into these classes. A further complication has been pointed out by Oguti (1968) who notes that several discontinuities may occur between the initial impulse of a storm and the main phase and the largest of these will be selected as the ssc, thus possibly giving $A > .8$ when the event might more appropriately be denoted as si. Thus, when space observations are related to a ground impulse, care should be used in characterizing the impulse.

Bowling and Wilson (1965) presented a collection of observations results, showing that ssc's and si's have 10 characteristics in common. They infer, as did others previously, that ssc and si are essentially the same phenomenon, both being caused by a sudden compression of the magnetosphere as the result of a discontinuous change of the energy density in the solar wind.

Nishida and Jacobs (1962) showed that there are other rapid "world-wide changes" in the geomagnetic field which are not reported as sudden commencements or sudden impulses yet have the same form, manner of spreading over the earth, and distribution of magnitude as ssc's and si's. They are more similar to si's than ssc's in that they are usually not followed by increased magnetic activity. Nishida and Jacobs suggested that si's are nothing more than world-wide changes that are widely recognized because of their large size. Both positive and negative world-wide changes are observed with essentially the same probability. At least 90% of the days and at least 20% of all 1-hour periods that they examined contained one or more world-wide changes.

## IV. RelationsBetween Types of Geomagnetic Impulses and Interplanetary Discontinuities.

A. Relations Between Types. Let us define ssc by $A > .8$ and si by $A < -.8$, and ask whether there is a relation between the type of impulse ($ssc^{\pm}$, $si^{\pm}$) and a particular type of discontinuity.

$ssc^{+}$ - shock. Evidence for hydromagnetic shocks that caused an $ssc^{+}$ was presented by Sonett et al. (1964), Dryer and Jones (1968), Burlaga and Ogilvie (1969) and Chao, (1970). Conversely, Burlaga and Ogilvie (1968) showed that $ssc^{+}$ is a fairly reliable indication of a hydromagnetic shock. Taylor (1968), using only interplanetary magnetic field data, examined the causes of 36 events reported by ssc by most stations ($A > .5$) during 1965, 1966 and 1967. He found that a) 26 of these were likely to be caused by shocks, and b) 10 were not caused by shocks, and 5 of these had $A > .8$. Thus a sudden commencement is a very good indication of a shock, but there are exceptions.

$ssc^{+}$ - T.D. An example of a sudden commencement that was not caused by a shock is given by Taylor (1968) - an event classified as ssc and si by 42 and 3 stations, respectively. It was associated with a large decrease in B and a $>90^{\circ}$ change in the direction of B, and the positive geomagnetic impulse implies an increase in density; thus, the discontinuity must be tangential, with signature (-, +, ?). Such events are relatively rare, however. It should be noted that in this case the main phase immediately followed the impulse; thus it represents the type of storm which Oguti (1968) attributes to a "bubble" (driver gas) that is not preceded by a shock.

Gosling et al. (1967a) reported that a world-wide "sudden commencement" at 1223 UT on April 6, 1965 was associated with a discontinuity whose signature was (?, ?, -); they note that this could be a tangential discontinuity, and is not a fast shock. Lincoln (1966) shows that 26 stations identified the event as ssc (A:4, B:14, C:8), and 14 identified it as si (A:4, B:5, C:5), giving A = .3; the event is not clearly a sudden commencement.

<u>$ssc^-$</u>. As discussed above, it is not clear that there is such a thing as a workd-wide $ssc^-$. In any case, as Oguti (1968) pointed out, it would be very difficult to distinguish it from an $si^-$ that just happens to occur during a storm, particularly if the negative impulse happens to be larger than any associated positive impulse. Gosling et al. (1968) showed that an interplanetary discontinuity with signature (?, -, +) caused a negative impulse which they identified as a "relatively rare negative SC". However, this event was classified as $ssc^-$ by 16 stations and as $si^-$ by 15 stations (Lincoln 1965) which gives A =.03, so that we would not call it a sudden commencement. Akasofu (1964) discusses an event at 0718 UT on 10 January 1960 that was classified $ssc^-$ by 44 stations and $si^-$ by 12 stations, which gives A = .39. This is a case in which 2 world-wide impulses occurred. The positive impulse at 0610 UT was not reported, but the larger negative impulse was identified and associated with the geomagnetic activity that followed. Most reported $ssc^-$ are probably in this class, and could equally well be described as a $si^-$ which occurred after the positive impulse of an $ssc^+$. There appear to be no $ssc^-$ analogous

to $ssc^{+}$, with $A > .8$. In any case, there is no evidence for a $ssc^{-}$, even with $A > .5$, that is caused by a "reverse fast shock". The reverse shock identified by Burlaga (1970) was not associated with a geomagnetic impulse.

<u>$si^{\pm}$.</u> There are few reported observations of interplanetary observations associated with sudden impulses. Burlaga and Ogilvie (1969) show cases in which $si^{-}$ was caused by a tangential discontinuity across which the density decreased. There is no evidence supporting the suggestion of Sonett and Colburn (1965) that $si^{-}$ is caused by a reverse shock. Gosling et al. (1967b) show a (?, +, +) discontinuity at an $si^{+}$.

<u>"world-wide impulses"</u>. The causes of these have not been extensively studied, but they are probably due to tangential discontinuities. Gosling et al. (1967a) showed plasma data for 2 world-wide impulses, one negative, which were not reported as si (see Figure 10). The signatures, (?, +, -) and (?, -, 0) for the positive and negative impulse, respectively, clearly exclude shocks and suggest T.D.'s as the causes. Since a density change is usually opposite to the magnetic field change across a T.D. and since positive and negative changes in B are equally probable (see Section II), one should observe equal numbers of positive and negative world-wide impulses, in agreement with the observations (see Section III). From (1) below and Figure 11, we see that a change $\Delta\sqrt{p} \gtrsim 10^{-4}$ (dynes km$^2)^{\frac{1}{2}}$ which corresponds to $\Delta n/n \sim 2\sqrt{n}\,\Delta\sqrt{n}/n \gtrsim .4$, will produce an observable impulse ($\Delta H \gtrsim 10\gamma$). This in turn implies $\frac{\Delta B}{B} \approx \frac{\Delta n}{2n} \gtrsim .2$ , and it was shown that such

discontinuities occur at the rate of ~3/day, which is on the order of the rate of occurrence of world-wide impulses (Section III). Thus, it seems likely that world-wide impules are due to T.D.'s. This supports the suggestion of Nishida and Jacobs (1962) that world-wide impulses are the same as si's.

B. Relation Between the Size of the Impulses and the Interplanetary Discontinuity. Parker (1958) pointed out that a discontinuous increase in the momentum flux of the solar wind would cause a compression of the earth's magnetic field which gives an increase in the field intensity at the earth's surface. The induced field has the same magnitude, $\Delta B$, and occurs nearly simultaneously at all points of the earth (see Williams, 1960 and Sato, 1961). To zeroth approximation, it is oriented along the dipole axis, so the corresponding change in the horizontal component of the earth's field, $\Delta H_{obs}\lambda = \Delta B\cos\lambda$ where $\lambda$ is the latitude of the observer. It is generated primarily by currents flowing on the surface of the magnetosphere and enhanced by the diamagnetic earth (See the review of Parker (1962), the recent analysis of Siscoe (1966) and the pioneering paper by Chapman and Ferraro (1931)). Siscoe et al. (1968b) give the following expression for $\Delta B$, from the magnetosphere model of Mead (1969):

$$\Delta B = A(\sqrt{P_2} - \sqrt{P_1}) \qquad (1)$$

where $A = 26.1 \times 10^4 \gamma/(\text{dyne/cm}^2)^{\frac{1}{2}}$ and, $P = b \times 1.16\ m_p n_p V_w^2$

where b ranges from .88 for $\gamma = 5/3$ to .955 for $= 1.2$ ($\gamma \equiv$ adiabatic exponent), $n_p \equiv$ proton density, $V_w \equiv$ bulk speed, and the helium density is taken to be 4% of the proton density to give 1.5 $m_p n_p$ for the total density. Using Mariner plasma data for 13 discontinuities associated with si's and world-wide impulses in the period December 1965-February 1966, Siscoe et al. (1968b) found that $\Delta B \sim A\Delta \sqrt{P}$ where $A \sim (9.0 \pm 2.) \times 10^4 \gamma /(\text{dynes/cm}^2)^{\frac{1}{2}}$. Similarly, Ogilvie et al. (1968) used plasma data from Explorer 34 for discontinuities associated with si's and ssc's during June 1967 to show that $\Delta B \sim A\ \Delta\sqrt{P}$ where $A = (11.4 \pm 1.5) \times 10^4$. Thus the linear relation given by (1) is confirmed. But the experimental value of A is less than $\frac{1}{2}$ the theoretical value; Siscoe (1970) suggests that this may be due in part to the presence of magnetospheric particles. The difference between the 2 experimental values of A is small ($\lesssim 20\%$) but might be real.

Ogilvie et al. did not consider that the size of the ssc impulse is enhanced on the day side of the earth at geomagnetic latitudes $\lesssim 20^\circ$ by ionospheric currents (see Sugiura, 1953, Jacobs and Watanabe (1963), Rastogi et al., 1966, Srinivasmorthy (1960), and Maeda and Yamamoto (1960). Correcting their work for this effect gives no significant change in the results in Figure 11.

Typically, $\Delta H$ is on the order of 30$\gamma$ or 40$\gamma$ for ssc, but Bhargava and Natarajan (1967) describe an event on November 13, 1960 with $\Delta H$=368 at Trivandrum, 220$\gamma$ at Kakioka and 211$\gamma$ at Alibag. Using the lower values and (1) we find $\Delta(nV_w) \sim 1.5 \times 10^9$. For a strong shock, with $n_2 = 4n_1$, and for the extreme case $V_2 \sim 3V_1 \sim 900$ km/sec this implies $n_1 \sim 10^2 \text{cm}^{-2}$, which is a very high density. They also note the events of 17 July 1959 and 11 July 1959 for which $\Delta H \sim 127\gamma$ and $102\gamma$, respectively, seen at night at Trivandrum.

Further studies of the relation (1) should be undertaken to better understand the currents which relate the surface effect to the interplanetary cause. Once the earth's field is thus calibrated, one can analyze the interplanetary discontinuities which left their imprint on magnetograms in the pre-satellite era.

Rise Time. The change, $\Delta H$, in a geomagnetic impulse occurs over a relatively long time interval, ~1-5 min, which is called the rise time. There are at least 3 explanations for this: 1) Nishida (1964, 1966b) suggested that the rise time for ssc is determined by the nature of the interplanetary discontinuity, 2) Dessler et al., (1960) and Francis et al. (1959) suggested that it is determined by the time it takes hydromagnetic waves to propagate through the magnetosphere from the various parts on the surface of the magnetosphere, 3) Sugiura suggested that it is determined by the transition from the initial state to the final state in the outermost region of the magnetosphere.

Nishida (1964) related rise time of ssc to an indirect determination of $V_r = V - V_w$, the discontinuity's mean speed between the sun and the earth relative to the solar wind speed. He distinguished between 2 kinds of ssc, - those with $V_r \gtrsim 600$ km/sec, which were associated with short rise times ($\lesssim 2$ min) and those with $V_r \lesssim 600$ km/sec, which were associated with larger rise times ($\gtrsim 2$ min). He attributed the former to shocks, the latter to non-shock mode discontinuities. If we assume that his ssc's correspond to $A \gtrsim 8$, there is clearly a disagreement between his inference and the conclusion in Section IV concerning the general cause of ssc. There is another problem: there is no hydromagnetic discontinuity other than a shock which propagates with speeds (100-500) km/sec relative to the solar wind, as does Nishida's non-shock mode. Finally, Nishida assumed that the rise time is determined primarily by the thickness of the interplanetary discontinuity, but some evidence by Burlaga and Ogilvie (1968) argues against this.

The quantitative theory of Dessler et al. (1960) is 2-dimensional and based on the geometrical ray approximation. Stengelman and Kenschitzki (1964) extended the theory using a 3-dimensional model and found that it could not explain the shape of the impulse, because of the inadequacy of the ray approximation.

Sugiura's explanation implies that the rise time should be essentially the same everywhere in the magnetosphere, in agreement with the Explorer 12 results of Nishida and Cahill (1964). The faster the shock, the shorter the transition time (see the illustrative calculation of Spreiter and Summers, 1965) and thus the shorter the rise time. A faster shock is also a stronger shock for a given solar wind speed, which implies a larger momentum change $\Delta P$ and thus a larger impulse $\Delta H$. One concludes, then, that the theory implies an inverse relation between the rise time and H for ssc. Pisharoty and Srivastava (1962) showed that such a relation does exist for the ssc's at Alibag between 1949 and 1960 (Figure 12). Chapman and Bartels (1962, p. 297) suggest no such relation, however, on the basis of the points shown as X's in Figure 12.

To really understand the rise time a good model of the propagation of an impulsive disturbance through the magnetosphere is needed. There are many models (e.g. Hines and Storey, 1958; Hines, 1958, Ferraro et et al., 1956, Willis, 1964) but we shall not pursue the subject.

C. "<u>$SI^+$ - $SI^-$ Pairs</u>".

<u>Geomagnetic Observations</u>. Sugiura et al. (1963) pointed out that world-wide impulses often occur in pairs consisting of a small positive impulse with $\Delta H \sim 5\gamma$ followed approximately 1 hour later by a similar negative impulse. Figure 13 shows an example of such a pair.

Akasofu (1964) pointed out the existence of another type of pair of impulses characterized by a large ($\sim 40\gamma$) positive impulse (not necessarily $si^+$) followed several hours later by a similar negative impulse. He showed 4 such pairs, each of which was followed by geomagnetic activity.

A typical giant pair is shown in Figure 14. Sonett and Colburn (1965) introduced the term "$SI^+$ -$SI^-$ Pair" to describe both kinds of impulse pairs, but they distinguished between "giant pairs" and "regular pairs". The term $SI^+$-$SI^-$ pair is quite misleading and is best not used at all. The distinction between giant and regular pairs is, however, sound and useful.

<u>Causes of Giant Pairs</u>. Sonett and Colburn (1965) suggested that giant pairs are caused by a pair of convected shocks. One of these is an ordinary fast shock moving away from the sun and causes the positive impulse; the other, which causes the negative impulse, is a reverse fast shock. The theory of such shock pairs was developed

by several authors (Simon and Axford, 1966; Sturrock and Spreiter, 1965; Schubert and Cummings, 1967, 1969). The most extensive model is that of Hundhausen and Gentry, 1969 who concluded that flare-associated forward-reverse shock pairs at 1 AU are not likely. Dessler and Fejer (1963) speculated that such shock pairs might appear at corotating streams in the solar wind. Razdan et al. (1965) noted the apparent ~27 day recurrence of giant pairs in magnetograms and extended the Dessler-Fejer speculation to explain them.

Despite the extensive theoretical work, there is no direct evidence for a shock pair in the solar wind. Schubert and Cummings (1967, 1969) suggested that the shock seen on October 8, 1962 was one of a pair, but the contact discontinuity and trailing shock were not seen, and the features which they somewhat arbitrarily fit to the shock pair model are very similar to those that are commonly seen at high speed streams even when no shock is present (Burlaga and Ogilvie, 1969; Ogilvie et al. 1968).

Ogilvie et al. (1968) presented plasma and magnetic field data associated with a giant pair, which showed that the positive impulse was due to a shock and the negative impulse was due to a tangential discontinuity across which the density decreased (see Figure 14). Such a combination-a shock followed several hours later by an abrupt decrease in density - is frequently seen proceeding high speed streams (for examples, see Burlaga and Ogilvie (1969), Ogilvie et al. (1968) and Lazarus et al. (1970). This suggests that giant pairs are generally caused by such driven shocks, the positive impulse being due to the shock as in an ordinary sudden commencement and the negative impulse being due to the discontinuity which sometimes separates the driver gas from the high density material that is piled up by the advancing stream. This discontinuity, then, would be analogous to that postulated by Parker (1963). The variety of possible giant pairs is reflected in the storm classification scheme of Oguti (1968).

The flow behind shock is usually not so simple, however, as evidenced by Figure 6, for example. Thus, the giant pair is just one of many types of geomagnetic signatures that can be produced by driven shocks, and the identification of the transition to driver gas is not always possible. The existence of several discontinuities behind certain shocks would be expected to be seen as si activity in the magnetograms. Yoshida and Akasofu (1966) have studied such events and related then to Forbush decreases. There are available many unpublished observations of the flow behind shocks. Because of their complexity, an analysis of them should be based on a collection which is as complete as possible.

<u>Causes of Regular Pairs</u>. The relation between regular pairs and interplanetary observations has not been studied. Burlaga and Ogilvie (1968) showed 2 dense spots in the solar wind associated with geomagnetic pulses for which they suggested the symbol pl. Such pulses may simply be closely separated pairs. Figure 1 (from Burlaga, 1968) shows a complementary pair of tangential discontinuities between when the density is high; such a feature may be expected to produce a regular pair. This is clearly an area of special interest, which requires further study.

**Summary**

The existence of fast shocks and tangential discontinuities in the solar wind is now fairly well established. Evidence for slow shocks and rotational discontinuities has been found, but needs to be corroborated. Double shocks have not been found, but a reverse shock has been identified. While much remains to be learned about the topology, distribution and origin of the various discontinuity surfaces, there is a substantial observational base for the study of the geomagnetic impulses which are generated by hydromagnetic discontinuities.

Although there is some confusion in the literature as to the types of geomagnetic impulses there are basically three types - $si^{\pm}$, $ssc^{+}$ and those which are not clearly si or ssc. World-wide impulses, are probably identical in essence to small si, and require no special classification; they deserve further study because they are an important means of monitoring density discontinuities on the solar wind. In general, $ssc^{+}$ is caused by a shock, although in some cases the most prominent discontinuity preceding a storm is caused by a tangential discontinuity. The relatively rare $ssc^{-}$ are caused by such tangential discontinuities and may generally be accompanied by a smaller positive impulse caused by a shock; thus, they may be better described as $si^{-}$. The $si^{-}$'s and world-wide impulses are probably usually caused by tangential discontinuities. Further studies of si's are needed.

The change in the H component of the earth's magnetic field is related to the change in the momentum flux in the solar wind. Further observations are needed to better define this relation, and a discrepancy with the existing theory needs to be resolved. The rise time of geomagnetic impulses seems to be determined by the propagation of the disturbance through the

magnetosphere rather than by the characteristics of the interplanetary discontinuity; this is a particularly interesting area for further study.

The subject of pairs of discontinuities("$si^+$-$si^-$ pairs" is extensive but confused. It is suggested that giant pairs are usually caused by a shock followed by a tangential discontinuity, while regular pairs are usually due to complementary tangential discontinuities.

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# FIGURE CAPTIONS

Figure 1 Two discontinuities in the interplanetary magnetic field. The abcissa is universal time. The ordinate gives the magnetic field intensity and direction in solar ecliptic coordinates, the plasma density, the thermal speed and the bulk speed. In this case the 2 discontinuities appear to define a "filament", but usually discontinuities are not paired.

Figure 2 A tangential discontinuity. The plane is a thin current sheet which separates 2 regions. The magnetic field vectors in the 2 regions are parallel to this plane, but otherwise arbitrary. The temperature and density of the particles may differ on side 1 and side 2, but the **pressure must** be the same in both regions. The material on side 1 may move along the plane relative to the material on side 1; hence, the term "glide plane" is used for the boundary.

Figure 3 A rotational discontinuity. The plane is an element of a real surface which can be measured in space. There is a component of $\underset{\sim}{B}$ normal to the surface. The field intensity does not change across the surface; thus, the tangential component of B appears to rotate in the plane through the angle $\alpha$. The density and temperature do not change across the plane. The plane of the discontinuity propagates relative to the plasma with the Alfven speed.

Figure 4 The distribution of the change in magnitude of $\mathbf{B}$ across discontinuities in the solar wind. The distribution on the left is based on Mariner 4 data and that on the right is based on Pioneer 6 data obtained a year later. The 2 distributions are essentially the same. The field intensity usually does not change across a discontinuity, and the change is seldom $\geq 20\%$.

Figure 5 Distribution of time intervals between successive discontinuities. Discontinuities with small changes in the magnetic field direction, $\omega$, occur most frequently.

Figure 6 This shows a series of discontinuities in the density in the flow behind a shock at 0610. The magnetic field data shows a corresponding pattern. Filamentary forms can be seen, but they are not unambiguous and are not all bounded by directional discontinuities. This figure shows the material that is piled up by an advancing stream of fresh, hot plasma.

Figure 7 The interplanetary magnetic field during a quiet period. Note that numerous discontinuities can be seen (marked by arrows), but it is not possible to describe the field by a unique series of step functions. Thus, the term "discontinuous" is appropriate, but it is an oversimplification to think of the field as a superposition of distinct filaments. However, some filamentary forms can be seen. The plot is based on 30 sec averages of the magnetic field; $\sigma$ is the standard deviation for each of the averages.

Figure 8 Definition of geomagnetic impulses in the H component of the earth's field. Events of type a) are positive impulses. Corresponding events with a decrease in H, rather than the increase shown in a) are negative inpulses. Other types of negative impulses, shown by (b), are less frequently seen.

Figure 9 Not all observatories classify an event in the same way. The number A describes the relative number of stations that identify an event as a sudden commencement or a sudden impulse. There are 2 classes of events, corresponding to si ($A = -1$) and ssc ($A = +1$), but many events cannot be unambiguously classified as ssc or si. Apparently ssc's are more easily recognized than si's.

Figure 10 The magnetogram traces show impulses that occurred world-wide, but were not identified as si or ssc by geomagnetic observatories. The corresponding plasma data suggests that these "world-wide impulses" were caused by the density changes at tangential discontinuities.

Figure 11 This shows that the change in the horizontal component of the earth's field (divided by $\cos \lambda$) is proportional to the change in the momentum flux across a discontinuity, as predicted. The difference between the 2 sets of observations might be a seasonal effect; this requires further study.

Figure 12 The rise time versus the change $\Delta H$ for ssc for data from Alibag (circles) and Batavia (crosses). Both an inverse relation and no relation have been suggested.

Figure 13 Pairs of impulses, such as that shown here, occur frequently. They have not been adequately studied in relation to solar wind observations, but are probably due to structures such as that in Figure 1.

Figure 14 The magnetogram trace shows a "giant pair". The corresponding plasma and magnetic field data show that the giant pair was caused by a shock followed by a tangential discontinuity. Such pairs may frequently appear with shocks driven by fresh, hot plasma from the sun. The high density material is probably compressed by the advancing stream; hence the second discontinuity of the pair may represent the transition between the driven and the driving gases.

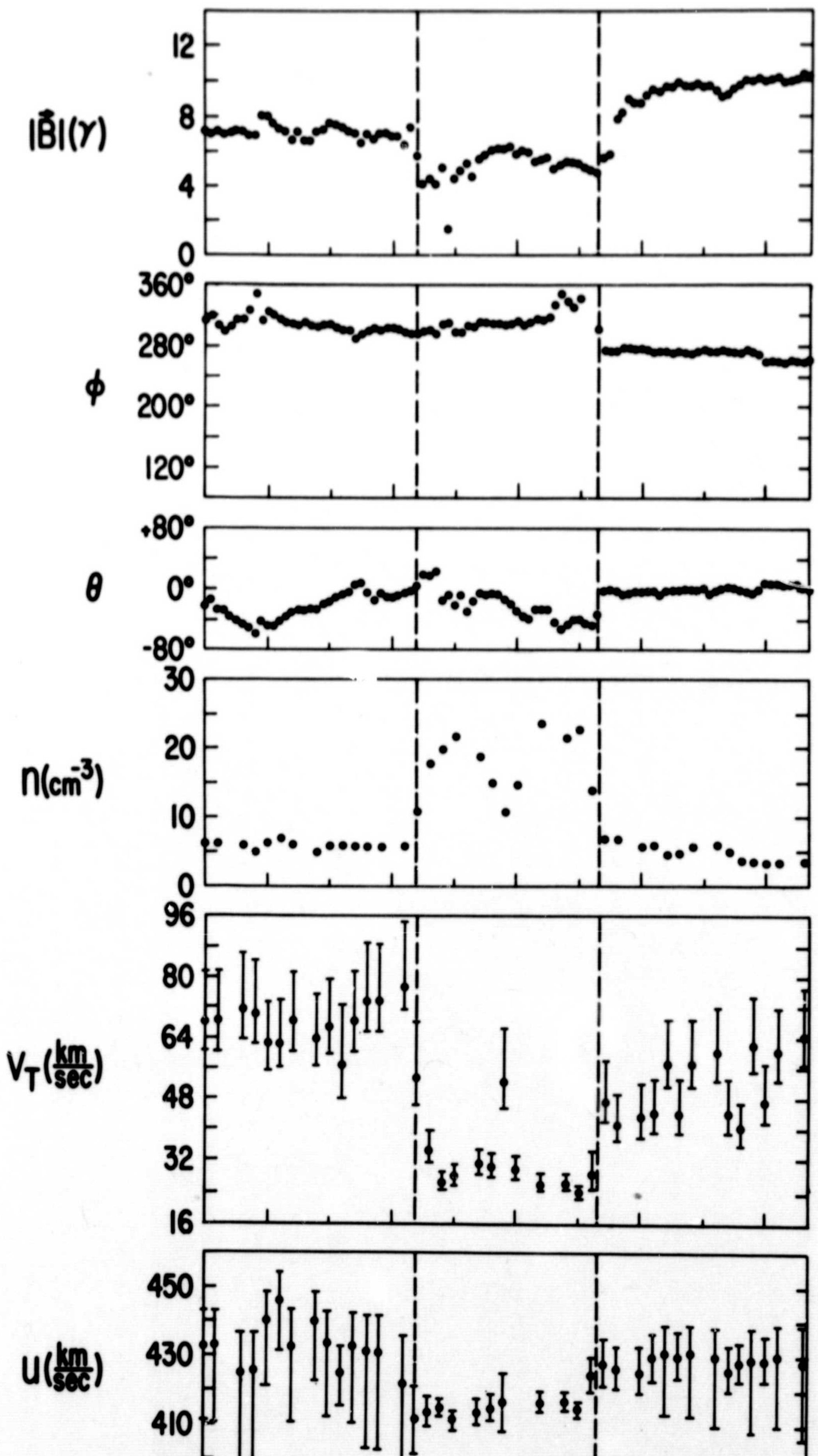
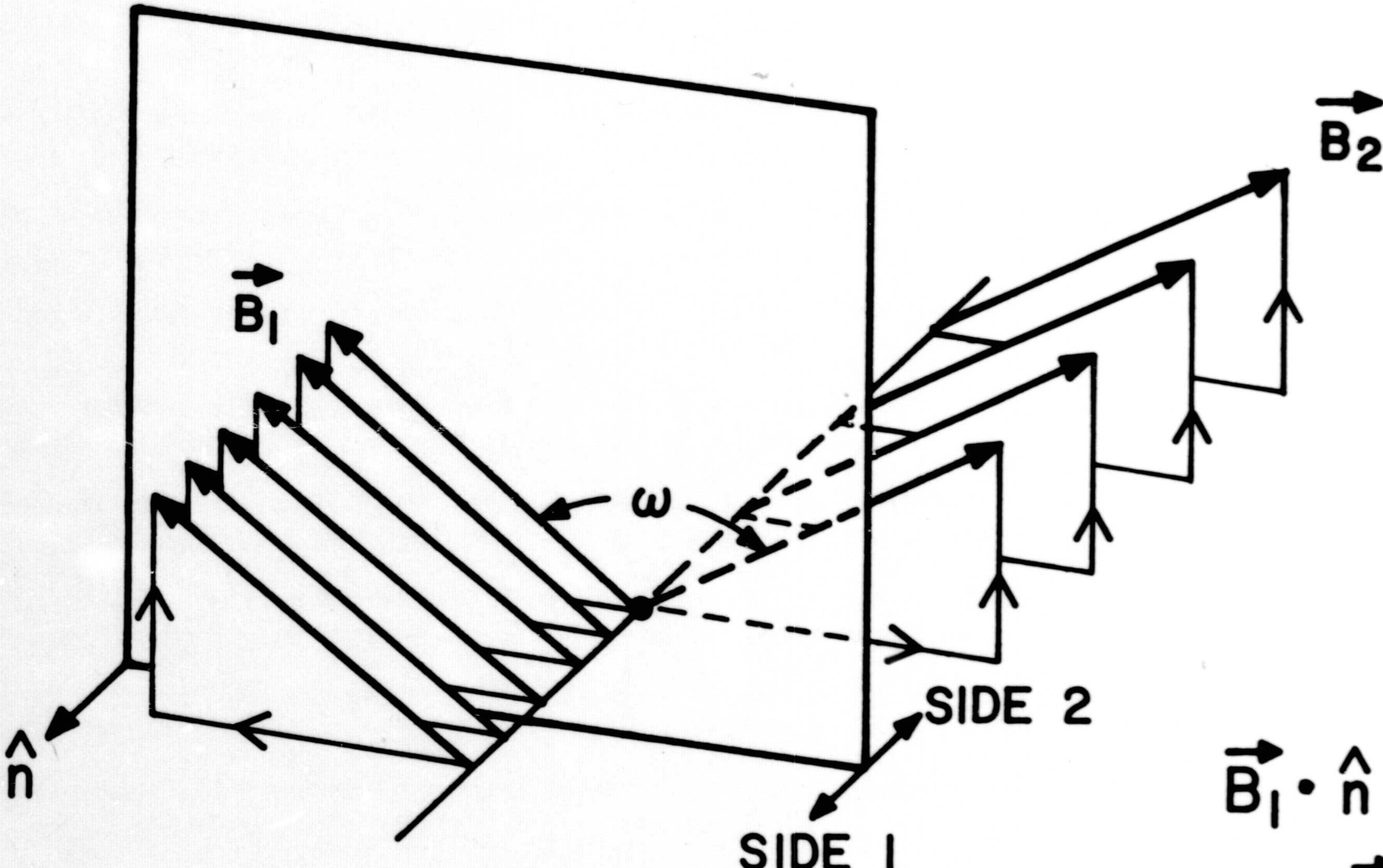



Figure 1

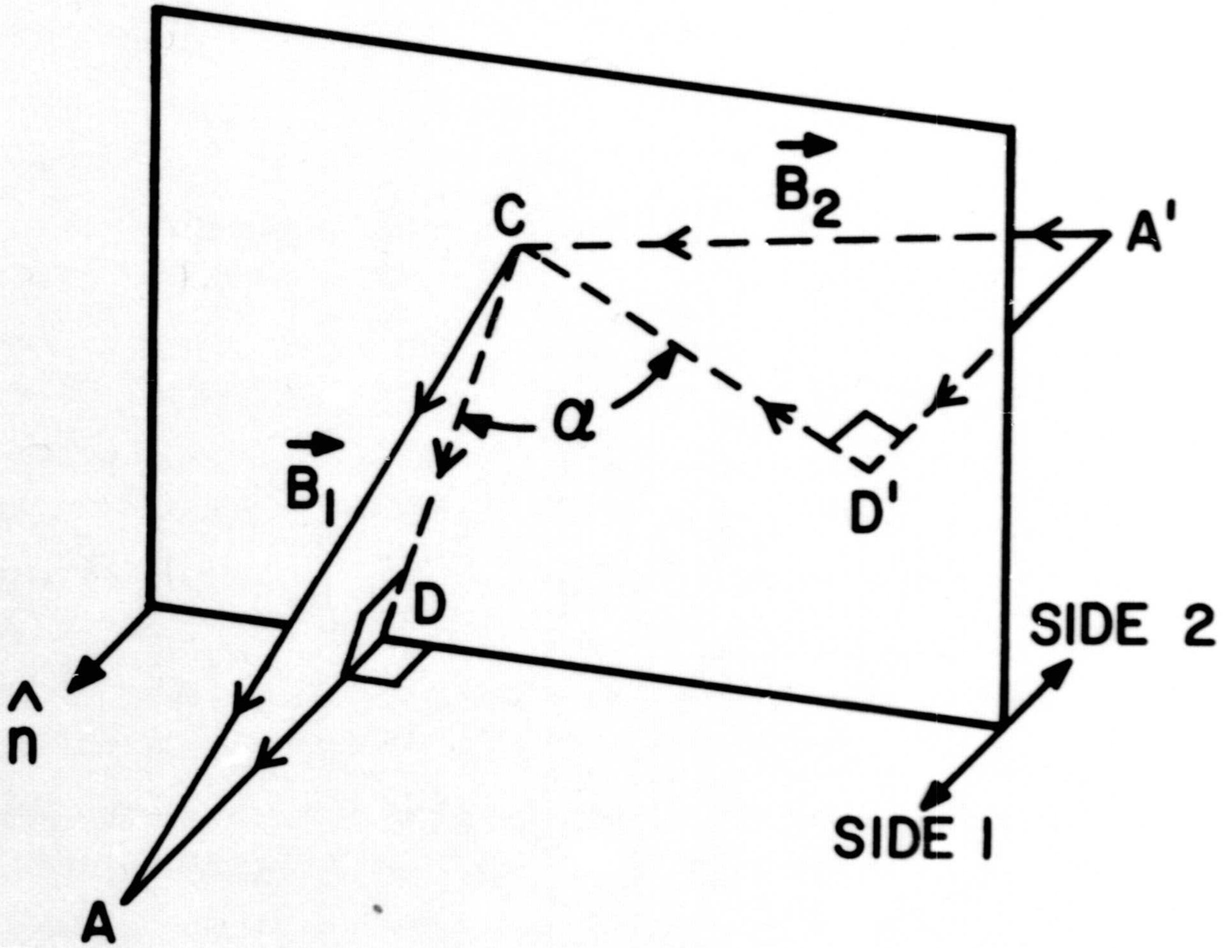



$$\vec{B}_1 \cdot \hat{n} = \vec{B}_2 \cdot \hat{n} = 0$$

$$\infty > |\vec{B}_1| / |\vec{B}_2| > 0$$

TANGENTIAL DISCONTINUITY

Figure 2




$$\left.\begin{aligned}\vec{AD} &\equiv (\vec{B}_1 \cdot \hat{n})\hat{n} \\ \vec{A'D'} &\equiv (\vec{B}_2 \cdot \hat{n})\hat{n}\end{aligned}\right\} 1$$

$$\left.\begin{aligned}|\vec{AD}| &= |\vec{A'D'}| \neq 0 \\ |\vec{B}_1| &= |\vec{B}_2| \equiv B\end{aligned}\right\} 2$$

$$\left.\begin{aligned}|\vec{CD}| &= |\vec{C'D'}| \\ 0° &\leq \alpha \leq 360°\end{aligned}\right\} 3$$

ROTATIONAL DISCONTINUITY

Figure 3

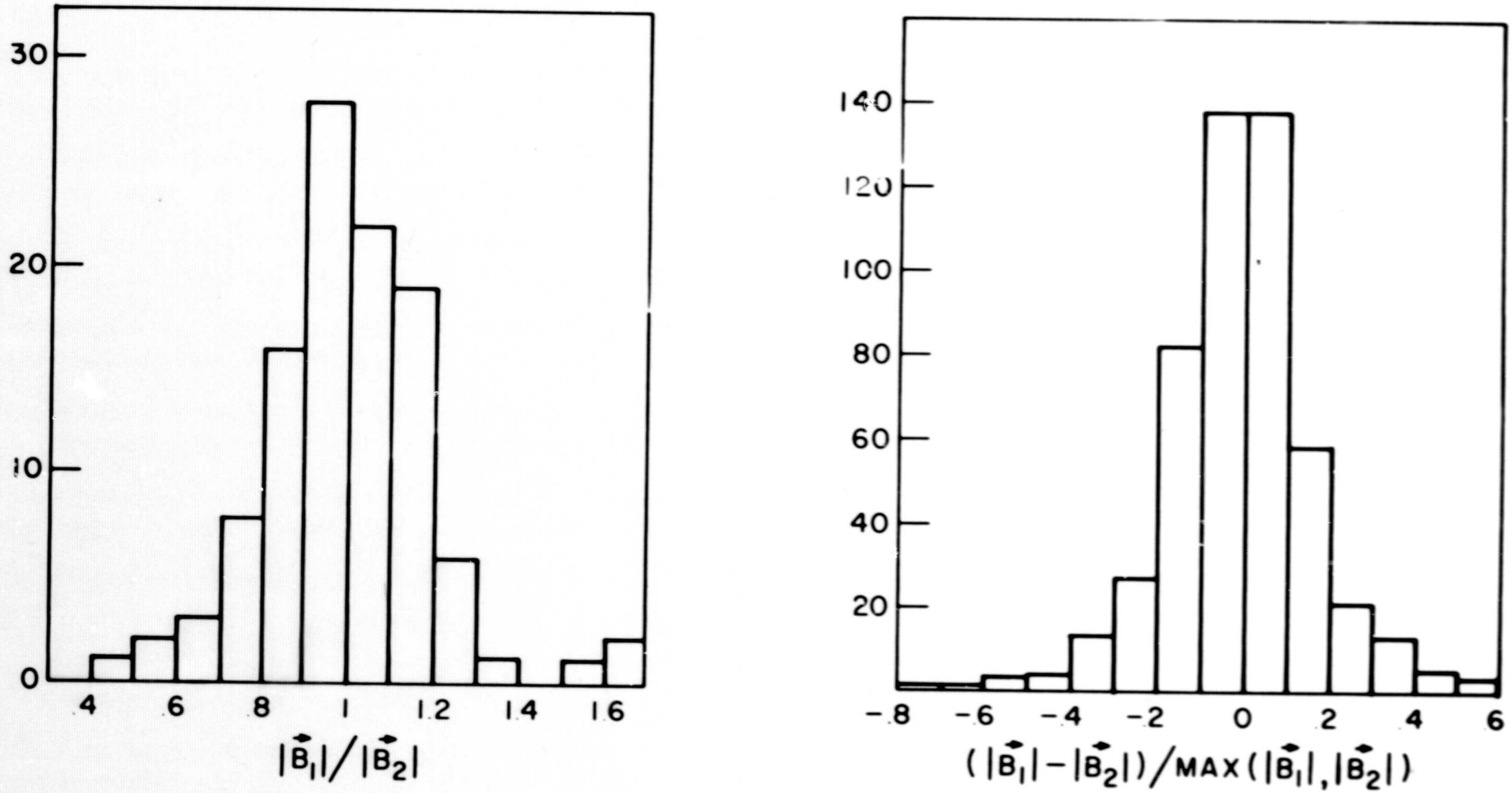
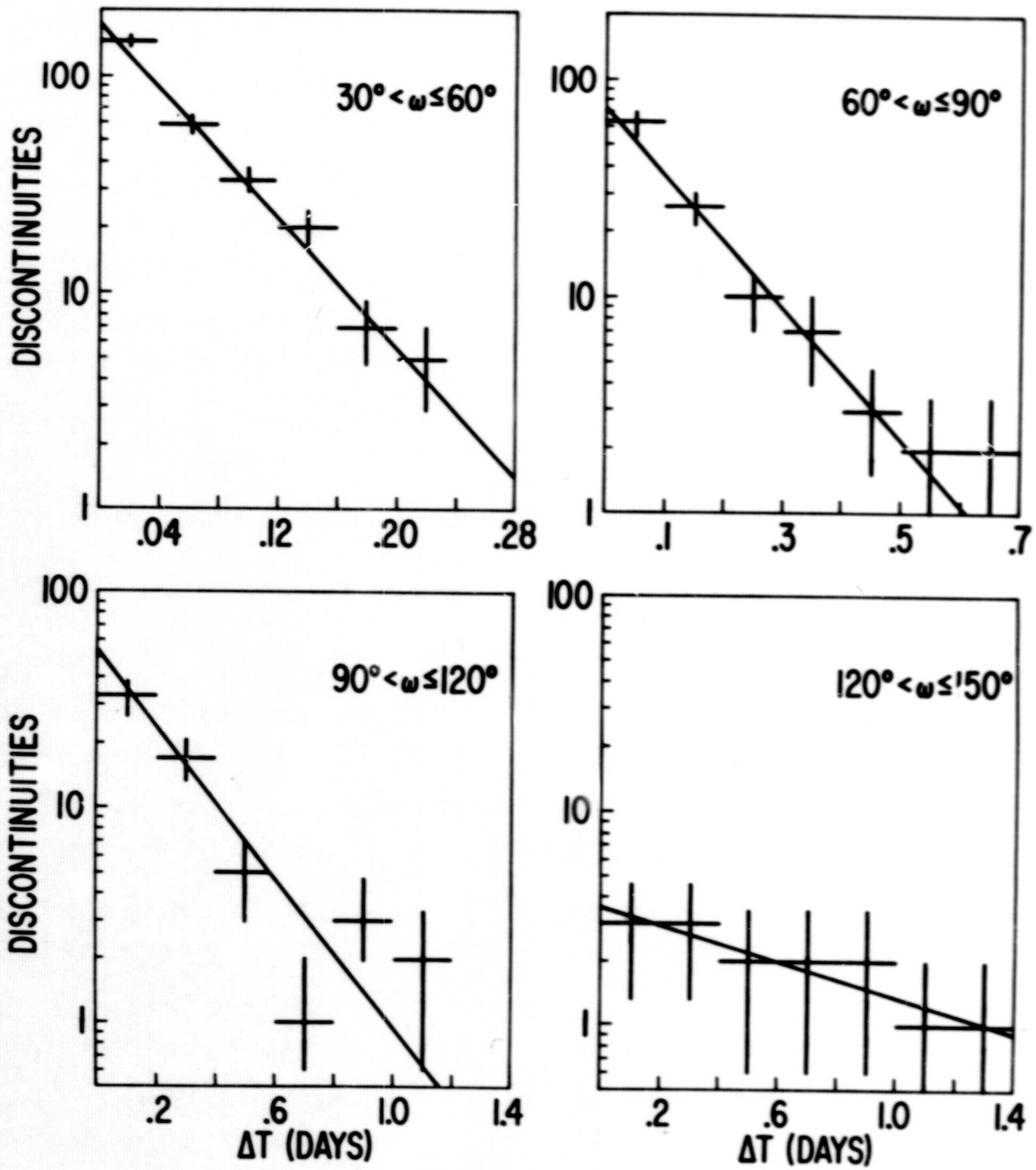
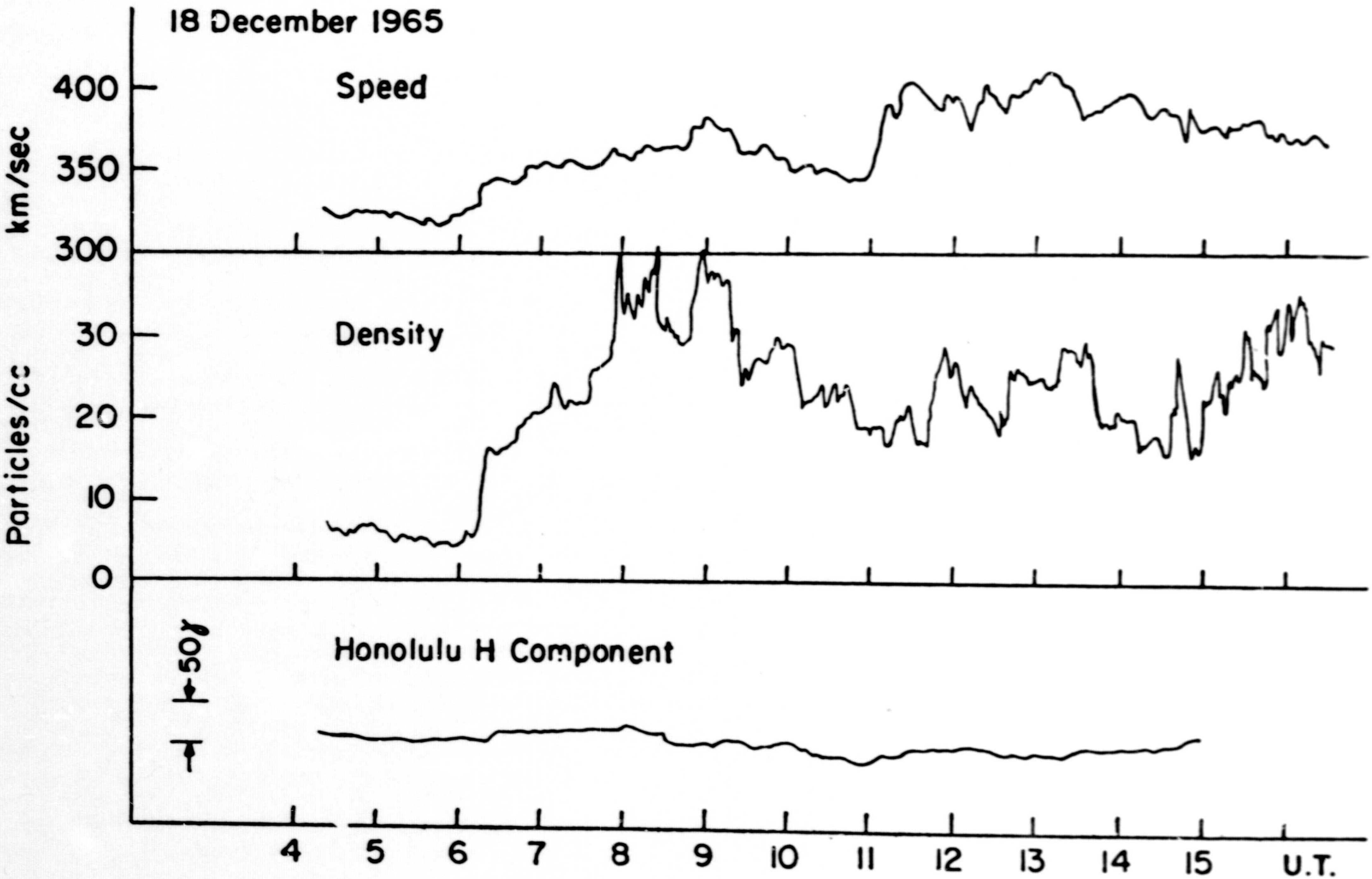

30
20
10
0
.4
.6
.8
1
1.2
1.4
1.6
$|\vec{B}_1|/|\vec{B}_2|$
140
120
100
80
60
40
20
-.8
-.6
-.4
-.2
0
.2
.4
.6
$(|\vec{B}_1|-|\vec{B}_2|)/\mathrm{MAX}(|\vec{B}_1|,|\vec{B}_2|)$

Figure 4



DISCONTINUITIES
100
10
1
30°<ω≤60°
.04
.12
.20
.28
60°<ω≤90°
.1
.3
.5
.7
90°<ω≤120°
120°<ω≤150°
.2
.6
1.0
1.4
ΔT (DAYS)


Figure 5



18 December 1965
Speed
km/sec
400
350
300
Density
Particles/cc
30
20
10
0
Honolulu H Component
50γ
4
5
6
7
8
9
10
11
12
13
14
15
U.T.


Figure 6

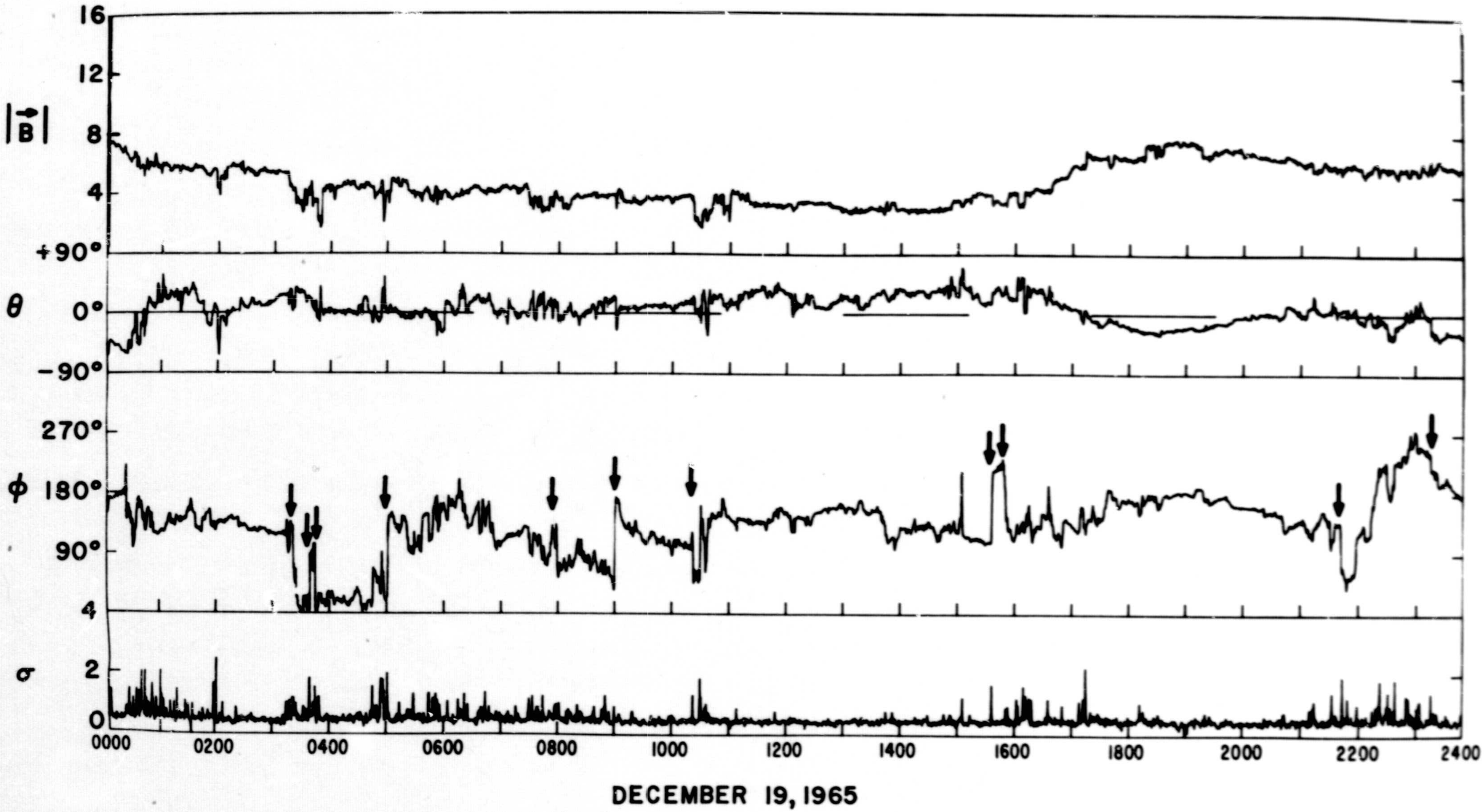

|B|
16
12
8
4
θ
+90°
0°
-90°
φ
270°
180°
90°
4
σ
2
0
0000
0200
0400
0600
0800
1000
1200
1400
1600
1800
2000
2200
2400
DECEMBER 19, 1965

Figure 7

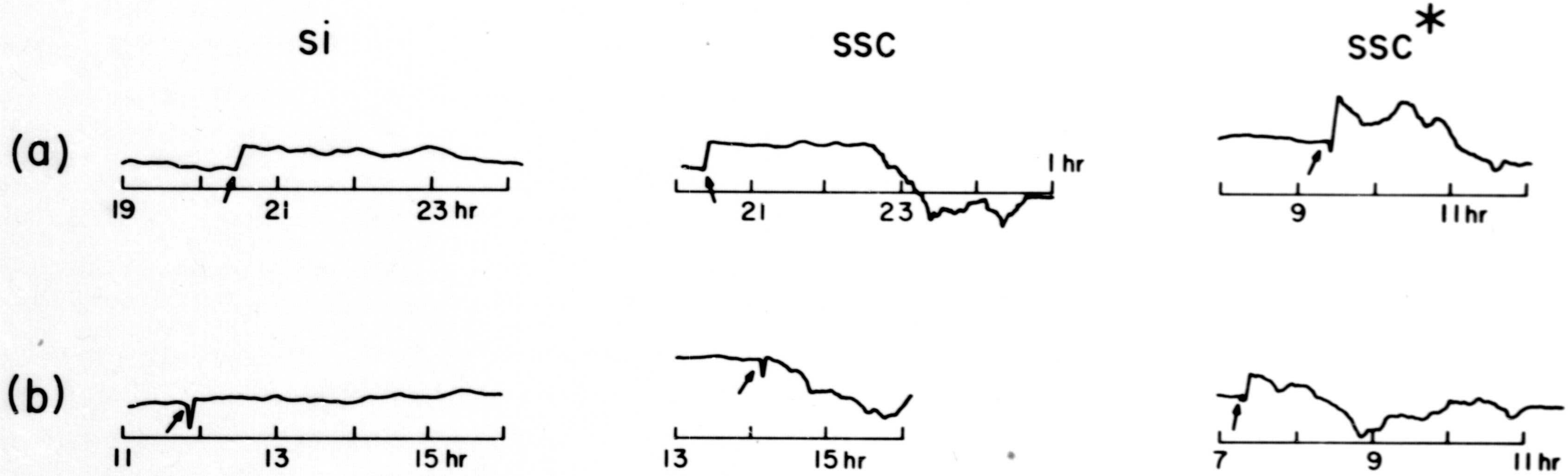



Figure 8

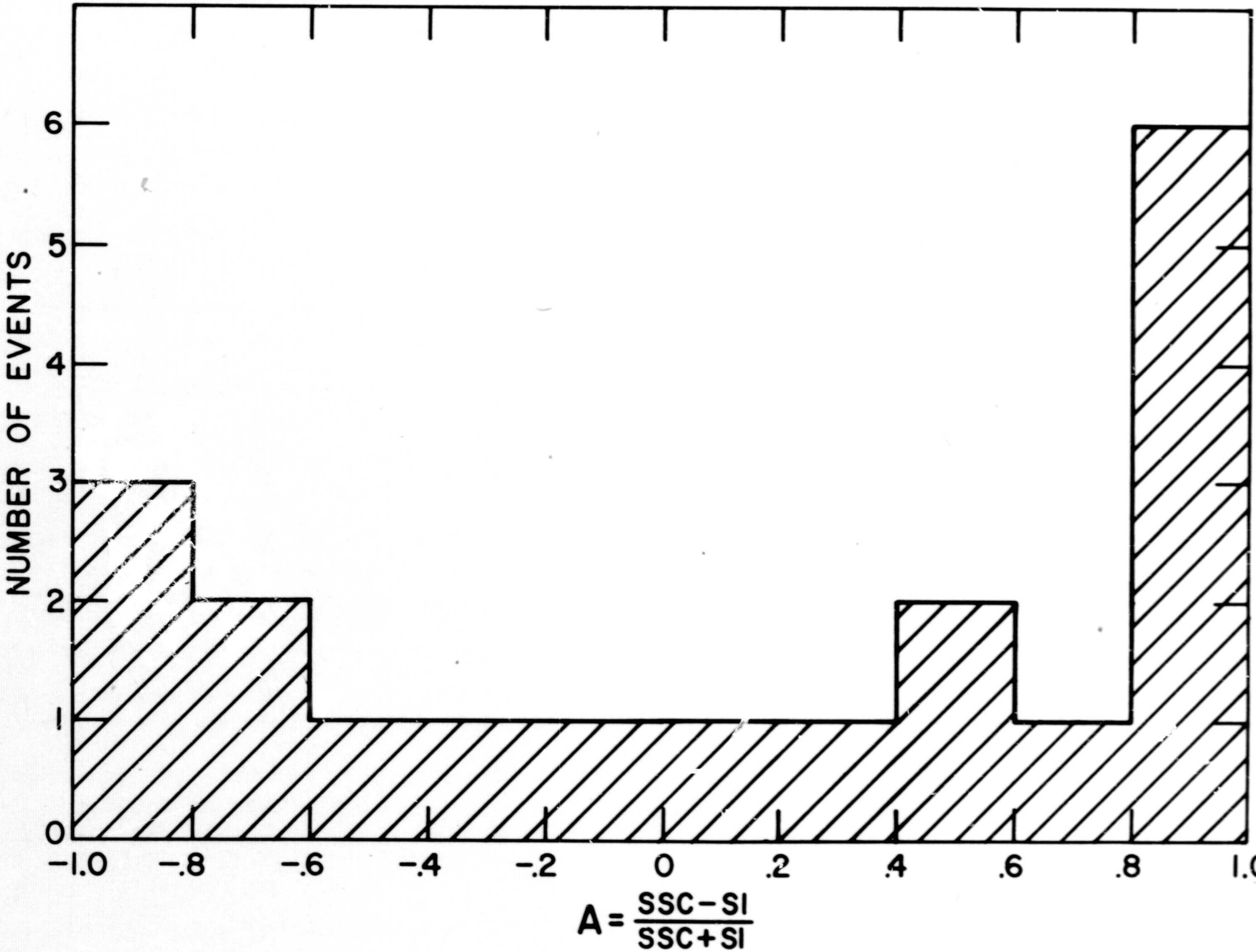
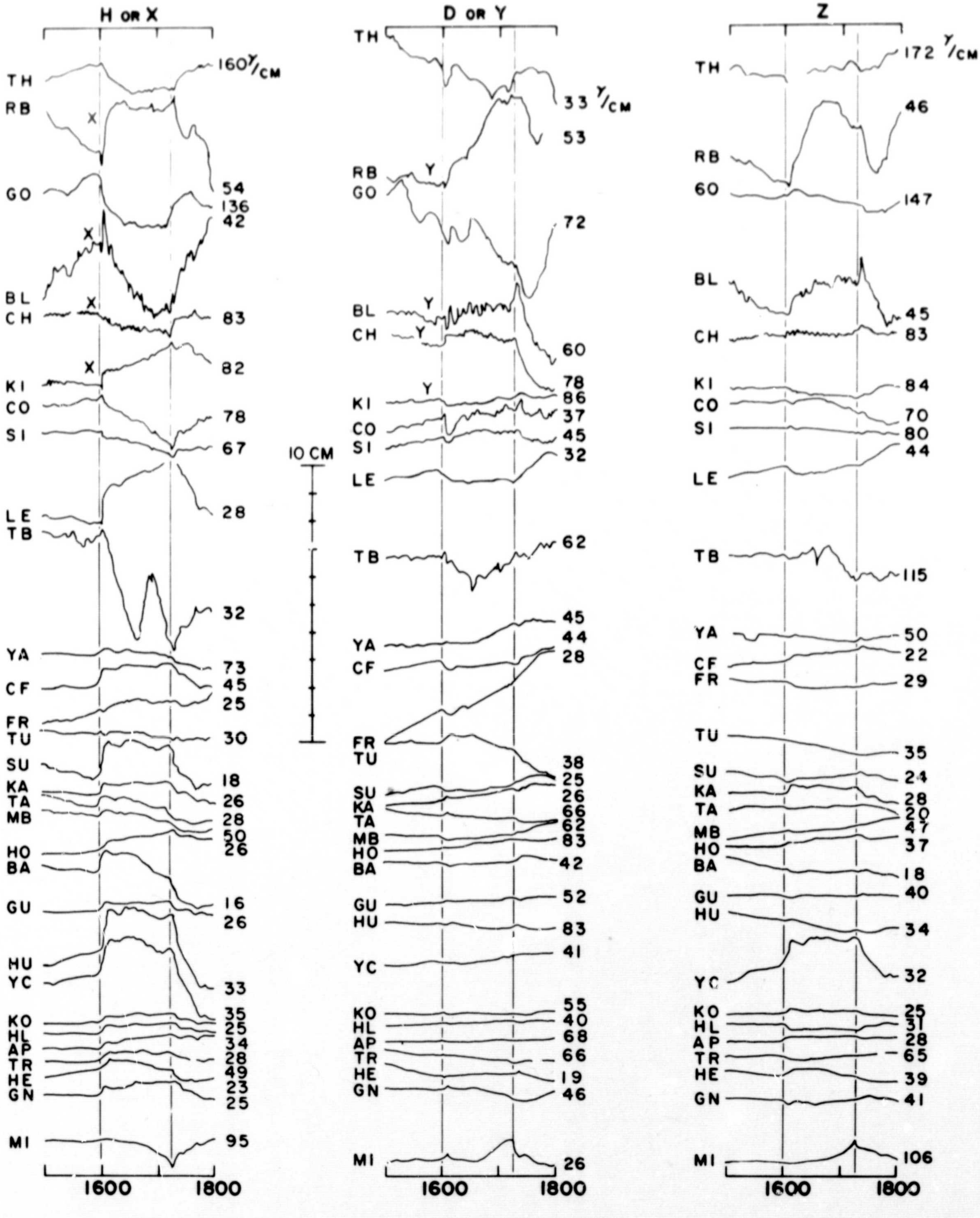
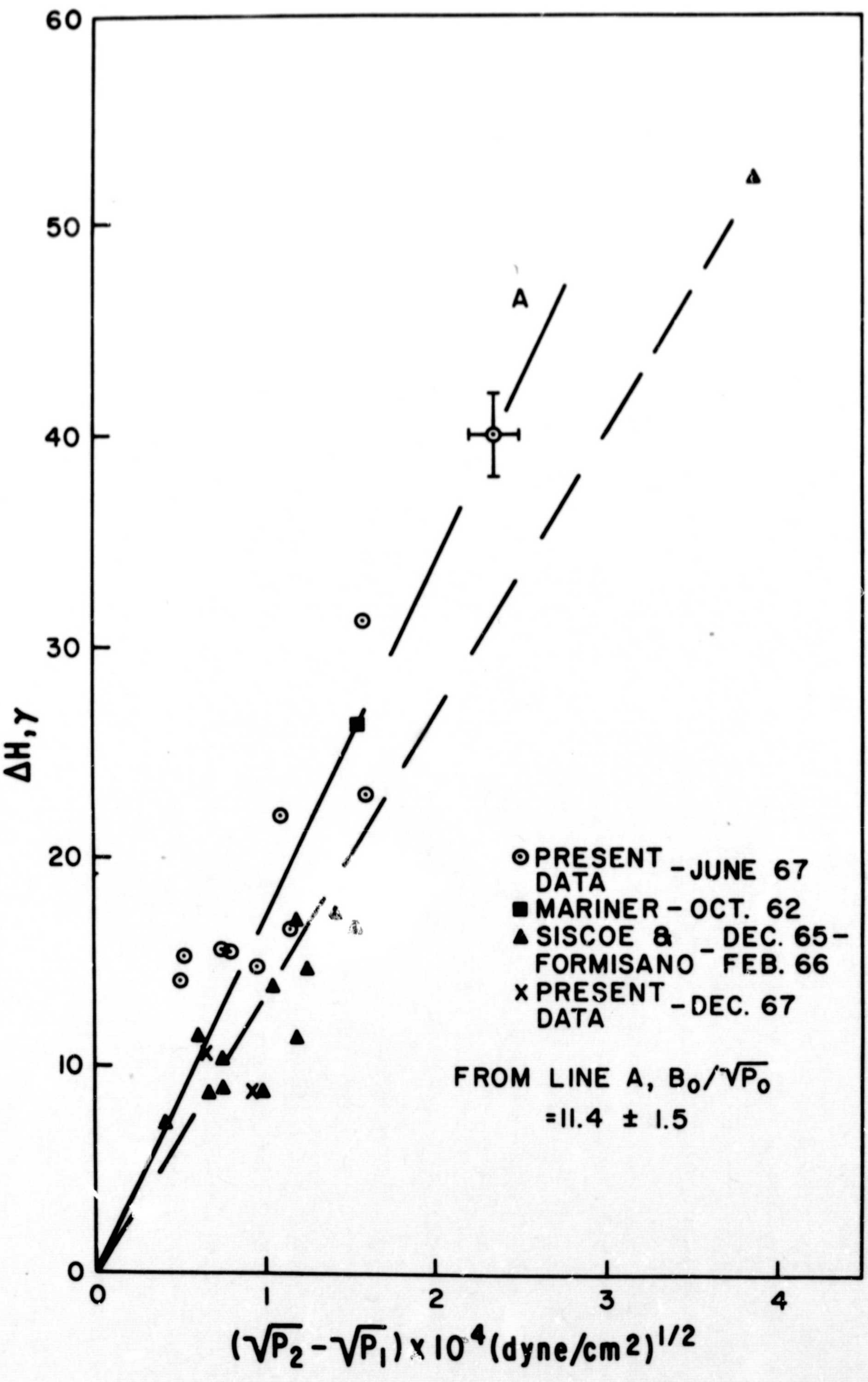



Figure 9



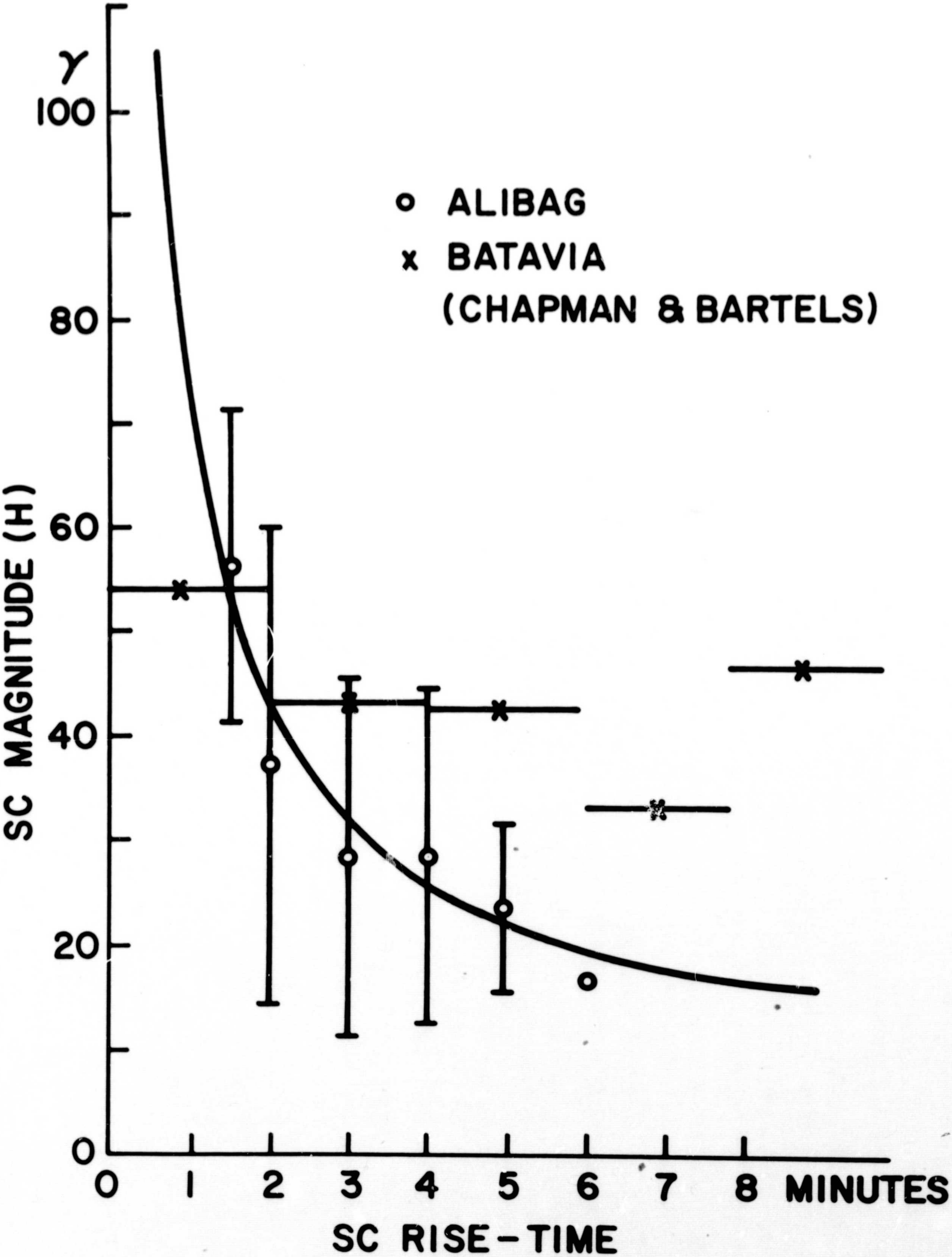

JUNE 19, 1958 (U.T.)

Figure 10



60
50
40
30
20
10
0
ΔH, γ
A
PRESENT DATA - JUNE 67
MARINER - OCT. 62
SISCOE & FORMISANO - DEC. 65 - FEB. 66
PRESENT DATA - DEC. 67
FROM LINE A, $B_0/\sqrt{P_0}$ = 11.4 ± 1.5
0
1
2
3
4
$(\sqrt{P_2} - \sqrt{P_1}) \times 10^4 (\text{dyne/cm}^2)^{1/2}$


Figure 11



γ
100
80
60
40
20
0
SC MAGNITUDE (H)
o ALIBAG
x BATAVIA
(CHAPMAN & BARTELS)
0
1
2
3
4
5
6
7
8 MINUTES
SC RISE-TIME


Figure 12

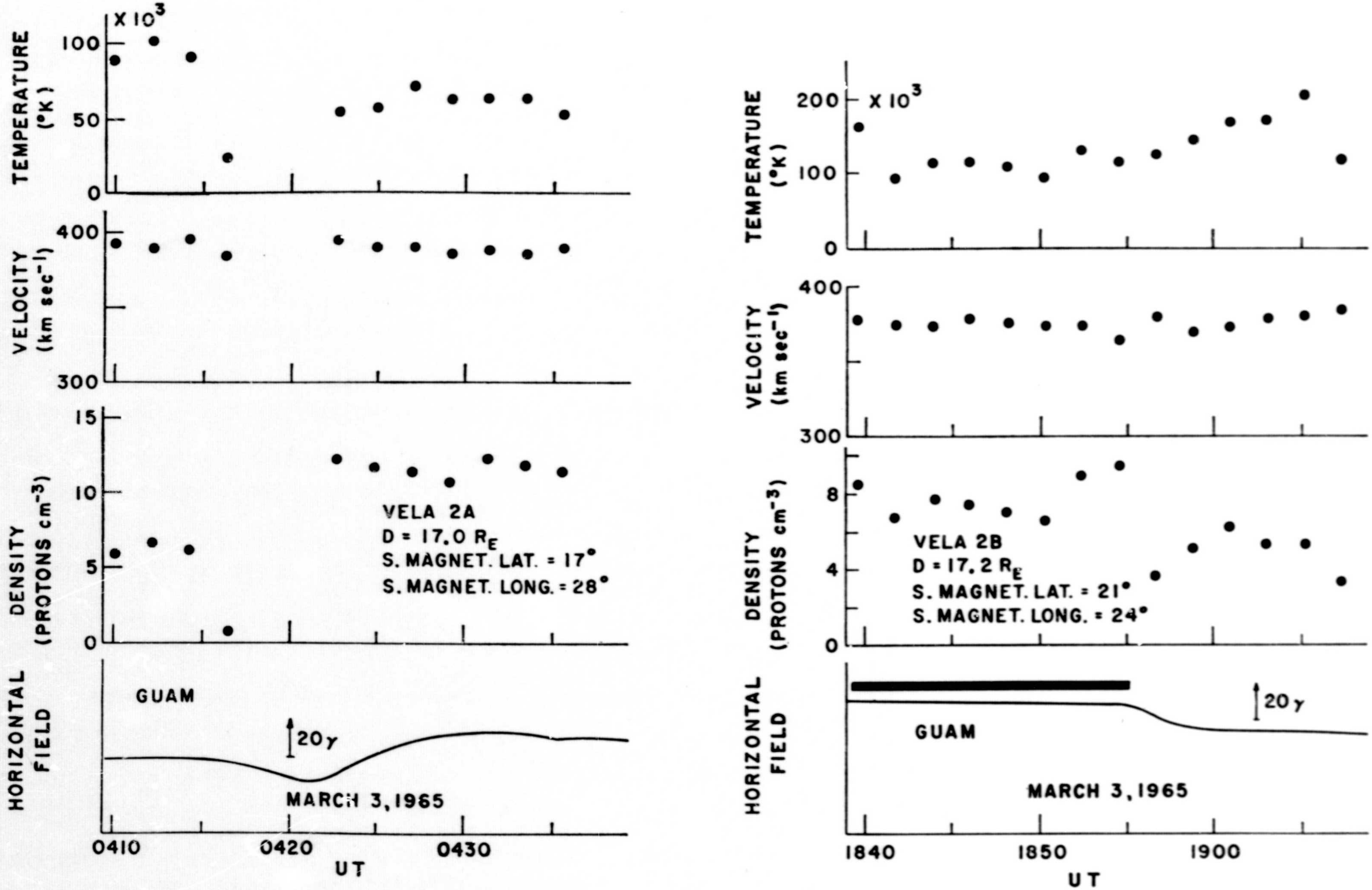
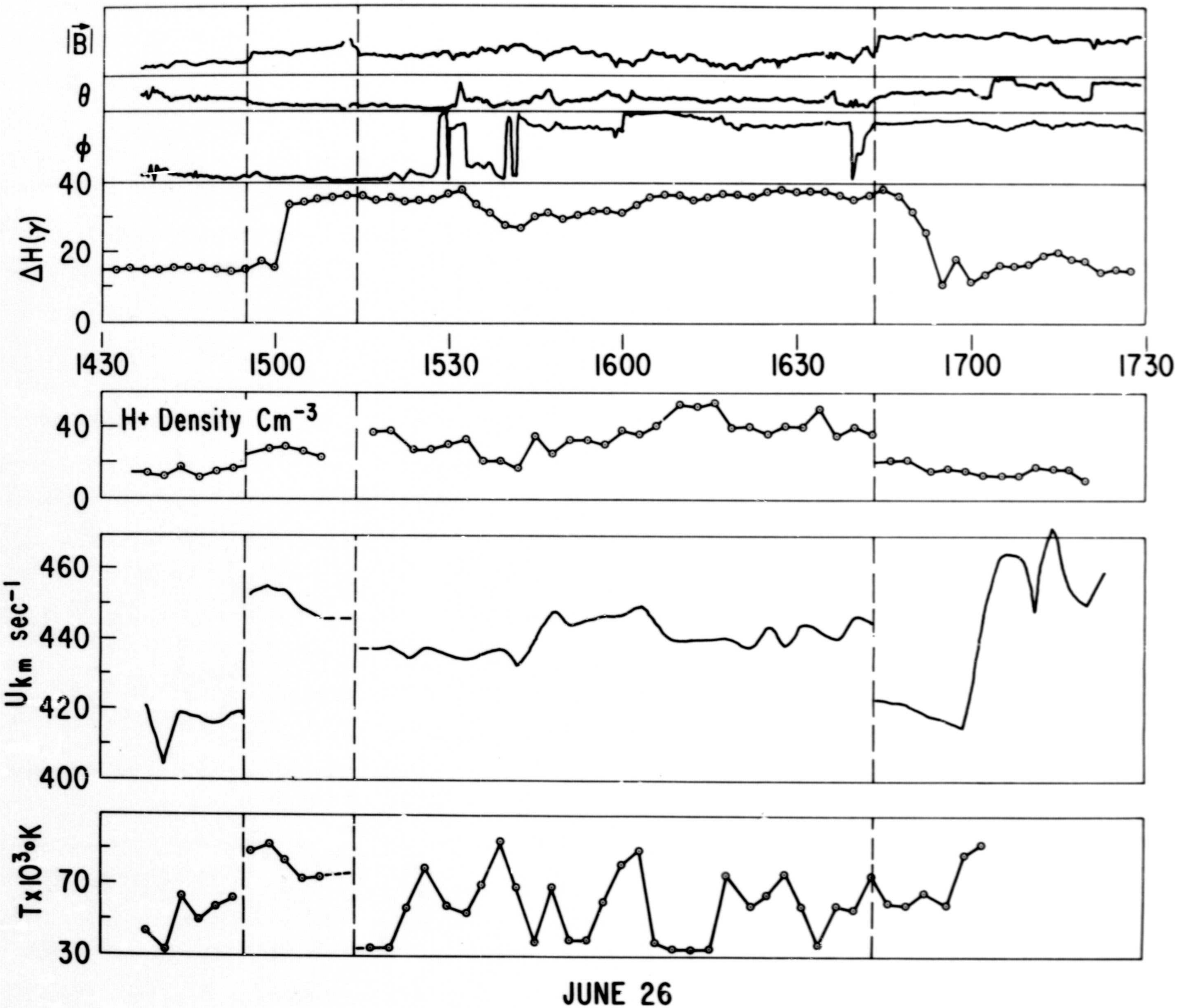

TEMPERATURE (°K)
X 10^3
100
50
0
VELOCITY (km sec^-1)
400
300
DENSITY (PROTONS cm^-3)
15
10
5
0
VELA 2A
D = 17.0 R_E
S. MAGNET. LAT. = 17°
S. MAGNET. LONG. = 28°
HORIZONTAL FIELD
GUAM
20γ
MARCH 3, 1965
0410
0420
0430
UT
TEMPERATURE (°K)
200
X 10^3
100
0
VELOCITY (km sec^-1)
400
300
DENSITY (PROTONS cm^-3)
8
4
0
VELA 2B
D = 17.2 R_E
S. MAGNET. LAT. = 21°
S. MAGNET. LONG. = 24°
HORIZONTAL FIELD
20γ
GUAM
MARCH 3, 1965
1840
1850
1900
UT

Figure 13



|B|
θ
φ
ΔH(γ)
40
20
0
1430
1500
1530
1600
1630
1700
1730
H+ Density Cm-3
40
0
Ukm sec-1
460
440
420
400
Tx10³°K
70
30
JUNE 26


Figure 14